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Sources of Ideas and Their Effectiveness in Parallel R & D Projects

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ABSTRACT

Seven sets of parallel R & D projects involving 15 laboratories are examined. Data gathered by Solution Development Records--a form which provides a weekly estimate of the probability of adoption of the approaches under consideration as possible solutions to a technical problem--and post-project interviews with the engineers responsible for each problem. The sources of technical approaches, indicated on the Solution Development Records, were obtained during the post-project interviews. Eight possible sources of ideas are considered.

Better performing groups are found to rely more than poorer performers upon information sources within the laboratory, for generation of ideas. A serious misalignment appears to exist between the quality of ideas generated through the eight channels and the frequency with which these channels are used by engineers. Vendors and analysis and experimentation, by the engineer himself, appear to be over-utilized relative to their effectiveness as idea sources, while information available from other company research programs and from the lab's technical staff is under-utilized.

The topic of this conference quite naturally directs one's attention to the process of information transfer - the generation, storage, summarization and retrieval of the ideas and data of science and technology. Information is both the raw material and the principal product of research and development, and as raw material, technical information is certainly one of the key determinants of research program effectiveness. As a result, a substantial effort has, in recent years, gone into the development of improved methods and systems to provide the researcher with the information he requires. Progress in this direction is dependent, however, upon our knowledge of the type and form of the information needed; the exact functions for which it is to be used; the mechanisms now available for performing these functions; and the inadequacies in the existing communication systems' performance for each function (Menzel, 1962).

The present paper considers the performance of the existing technical communication system in meeting one of its principal functions: the generation of technical alternatives for consideration as potential solu-

tions to R & D problems; it is based upon data gathered in a study of parallel R & D projects[1] which has been underway over the last two years.

To assist in obtaining a performance evaluation for specific information channels instances were sought out in which the same problem is attempted by two or more research groups. In this way, a comparison can be made between the information sources leading to specific solutions. The fairly common practice of the Department of Defense and the N.A.S.A. to award parallel study contracts during the early phases of R & D provides an opportunity for control over the effect of variations in the problem substance. The data presented are from seven parallel contracts involving 15 R & D groups.

METHODS

Once a parallel project has been located, its work statement is obtained and analyzed and factored into a reasonable number of subproblem areas (generally subsystems). The breakdown is then checked with the technical person who prepared the work statement, and data collection forms based upon it are designed. After all data have been collected from the contractors, the technical monitor is revisited and asked to provide a con-

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[1] The idea of studying parallel R & D projects as a quasi-experimental situation was suggested by Donald Marquis, who also helped in developing some of the research procedures.

fidential evaluation of each lab's performance on each subproblem. Data are gathered by four means: (1) time allocation forms, indicating the amount of time each engineer spends on the job in several activity categories; (2) before and after interviews with the individual engineers; (3) periodic tape recorded progress reports by the project manager; and (4) solution development records.

Post-project interviews, supported with the charted Solution Development Record, are the principal source of the data here under consideration. The Solution Development Record is a research tool which provides a record over time of the progress of an individual engineer or group of engineers (or scientists) toward the solution of a technical problem. The lead engineer responsible for each subproblem is asked to provide a weekly estimate, for each alternative approach under consideration, of the probability that it will be finally chosen as the solution to that subproblem.

Figure 1 illustrates the listing of alternative approaches identified from the contract work statement, when so specified, and from the responsible engineer when he is interviewed prior to beginning the task. Blank spaces are always provided so that new approaches may be reported as they arise. If at some point in the design the respondent were considering two technical approaches to rendezvous at Uranus, and he were completely uncommitted between the two, he would circle 0.5 for each, as shown. Eventually as the solution progresses, one alternative will attain a 1.0 probability and the others will become zero. By plotting the probabilities over time, we obtain a graphic record of the solution history.

FIGURE I

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Solution Development Record

Manned Uranus Landing in an Early Time Period Study

General United Aerospace Corporation

me ______________________ Date ______________________

Estimate of Probability that Alternative will be Employed

bproblem #1: Method of ndezvous at Uranus

ternative approaches:

orbital rendezvous mission with excursion vehicle	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
orbital rendezvous mission without excursion vehicle	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
direct mission	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
______________________	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

bproblem #2: Design of the ectrical power supply subsystem r the space vehicle

ternative approaches:

hydrogen-oxygen fuel cell	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
KOH fuel cell	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Rankine cycle fast reactor	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Rankine cycle thermal reactor	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Brayton cycle reactor	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
______________________	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
______________________	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
______________________	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

When the project is completed, each respondent is presented with a time-plot of his probability estimates, and is interviewed at some length to determine causes and effects of design changes reflected in this record. The plot thus provides a stimulus to the man's memory and assists the investigator in gathering a detailed record of each project.[2]

Description of the Projects

The seven projects under consideration, involved the following general problems:

1. The design of the reflector portion of a rather large and highly complex antenna system for tracking and communication with space vehicles at very great distances.
2. The design of a vehicle and associated instrumentation to roam the lunar surface and gather descriptive scientific data.
3. An investigation of passive methods for transfer of modulation between two coherent light beams.
4. A preliminary design of an earth-orbiting space station.
5. The design of a deep space probe, and appropriate instrumentation.
6. The preliminary design of an interplanetary space vehicle.
7. The preliminary design of a special-purpose manned spacecraft for cislunar missions.

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2 Solution Development Records were not obtained or were of poor quality for two of the seven projects. In these instances, engineers were asked to recap, as best they could, their solution process, including all technical approaches considered. Without the benefit of the stimulus which the solution development plot provides to the man's memory, some considered approaches may well have been missed. While this reduces the size of the sample, it should not bias it toward or away from specific channels.

Functions, Channels and Messages

While the technical communication system performs many functions for the engineer, the focus here will be on one: that of generating technical alternatives to the solution of R & D problems. Eight channels from which such alternatives can be obtained are considered (Table I). In addition to the six channels external to the engineering group, two sources of ideas (analysis and experimentation and personal experience), which are internal to the group are included in the analysis.

The unit of analysis employed is "messages received" (Menzel, 1960, pp. 20-22). In other words, the suggestion of a potential solution to the problem is considered a message received. Quite often a single alternative will result from messages received from several channels; for example, reference in the trade literature might lead the engineer to a vendor who provides more complete information on the alternative. In such a situation, where several channels contribute to a single alternative, credit is given to each source. Sources of alternatives were sought out in the post-project interviews, and the tape-recorded transcriptions of these interviews were coded to indicate channels through which each alternative was generated.[3] A total of 482 technical alternatives resulted from 610 messages received; 179 of these messages were finally accepted resulting in 117 problem solutions.

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[3] An inter-coder reliability of 80% perfect agreement was obtained for a sample of the transcriptions.

TABLE I

Information Channels Considered in the Study

literature:	books, professional, technical and trade journals, and other publicly accessible written material.
vendors:	representatives of, or documentation generated by, suppliers or potential suppliers of design components.
customer:	representatives of, or documentation generated by, the government agency for which the project is performed.
external sources:	sources outside the laboratory which do not fall into any of the above three categories. These include paid and unpaid consultants and representatives of government agencies other than the customer agency.
technical staff:	engineers and scientists in the laboratory who are not assigned directly to the project being considered.
company research:	any other project performed previously or simultaneously in the lab regardless of its source of funding.
personal experience:	ideas which were used previously by the engineer for similar problems are are recalled directly from memory.
analysis and experimentation:	ideas which are the result of an engineering analysis, test or experiment with no immediate input of information from any other source.

RESULTS

An example of a solution development plot is shown in Figure 2. In this instance, each group considered five alternative approaches to the problem. Three of these (α, β and γ) were specified by the customer at the start of the contract. Two were generated by each team during the course of the project. In team A approach δ had been previously used by the engineer on problems of a similar nature, and the association of this problem with the former ones brought the idea out of memory. Approach ϵ was suggested by a paper which a colleague had heard presented at a SAE meeting. Further details on this approach were obtained through the trade literature and vendors.

In team B an engineer, thumbing through a colleague's reference file of clippings from trade journals, ran across an item which suggested approach ζ to him. He had employed this approach before but it had not occurred to him as a possibility for this particular application until his memory was jolted by the trade journal clipping. Fortuitous contact with the representative of a vendor firm suggested approach η. This representative happened to visit a man in another department who knew of the engineer's problem and suggested that the vendor contact him. In a similar manner, alternatives considered in other subproblems are attributed to the information channels whence they originated.

The alternatives are evaluated at two levels. At the first level, the

TABLE II

Messages Received and Messages Accepted by R & D Engineers as a Function of Information Channel

	channel	messages received	messages accepted	acceptance ratio
channels outside the laboratory	literature	45	14	0.31
	external sources	50	24	0.48
	vendors	80	25	0.31
	customers	99	23	0.23
channels inside the laboratory	technical staff	27	13	0.48
	company research	23	13	0.57
	analysis and experimentation	164	47	0.29
	personal experience	50	15	0.30
	unknown	72	5	---

engineer himself decides upon one of several possibilities as the best solution to the subproblem; he thus evaluates this alternative as preferable to the others under consideration. At a second level, for at least some of the subproblems, a relative evaluation by the customer of the solutions reached by the two or three research groups on each problem is available. So, for each problem, two or three alternatives are first chosen over all others by the R & D groups and then these two or three are evaluated relative to each other by the government technical representative. Working backward to the sources of the alternatives provides two measures of performance for the information channels.

Acceptance by the Engineer

Table II shows total frequency counts for messages received and accepted from each of the eight channels. Seventy-two alternatives could not be attributed to a channel, either through the unavailability for interview of the knowledgeable engineer, or through failure to obtain this information during the interview.

These data show quite a diversity in both relative use and performance of the eight channels. A chi-square test performed on accepted and rejected (total-accepted) messages[4] shows a significant ($X^2 = 20$; $p<0.01$) difference in the allocation of acceptances and rejections among channels.

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[4] Alternatives of unknown origin are excluded.

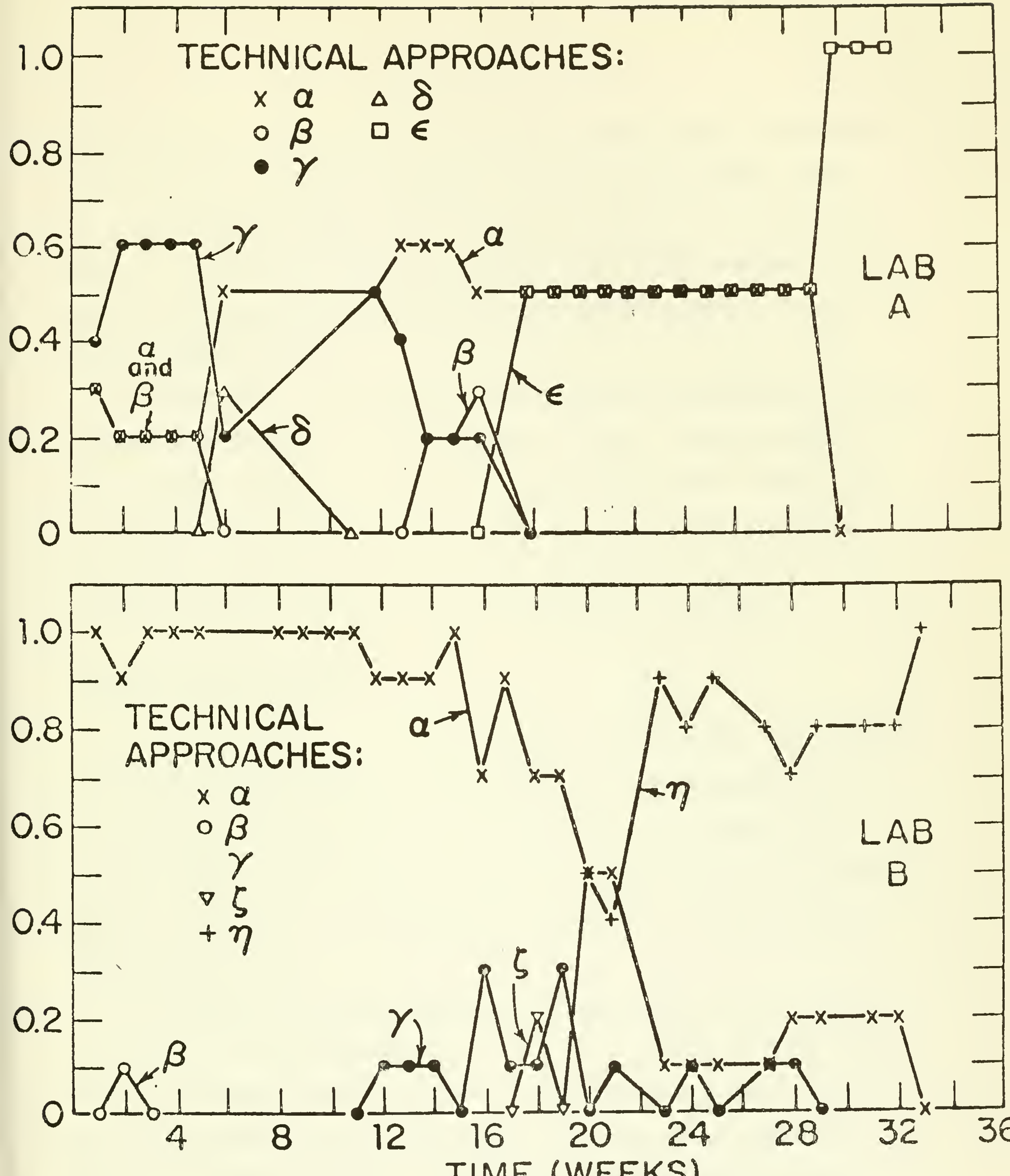

FIGURE 2

SIGN OF SUBSYSTEM TO DETERMINE ANTENNA POSITION.

External sources, technical staff and company research supply a considerably greater number of acceptable approaches than would be expected by chance, while the approaches suggested by the customer, and those arrived at through analysis or experimentation have a relatively low level of acceptance. The distribution of acceptances and rejections among other channels is rather close to chance expectation.

Interestingly, the acceptance ratios for the eight channels are inversely related to the degree to which the channels are used. Since some authors have suggested frequency of use itself, as an index of channel value, with the assumption that a researcher's behavior implicitly recognizes quality, the finding of an inverse relation between frequency of use and this first measure of channel performance is surprising and rather important.

Evaluation by the Customer

For 16 of the 63 subproblem pairs, relative evaluations of the solutions were obtained from responsible technical monitors in the customer agencies. In the remaining 47 pairs, scores were either tied or no evaluation was available. This relative evaluation permits a comparison of the information channels used to arrive at a solution judged superior to the solution presented by other teams.

The hypothesis to be tested here is based upon the findings of Allen (1964) for R & D proposal competitions. The use of information sources outside of the laboratory was found to be inversely related to the technical quality of proposals, while use of sources within the lab was weakly but positively related to quality. The hypothesis predicts that poorer per-

TABLE III

Sources of Higher and Lower Rated Solutions
(16 Subproblem Pairs)

	information channel	subproblems with higher rated solutions	subproblems with lower rated solutions
channels outside the laboratory	literature	3	4
	external sources	2	6
	vendors	6	5
	customer	12	11
channels within the laboratory	technical staff	2	1
	company research	3	1
	analysis & experimentation	11	10
	personal experience	3	3
	unknown	2	4

forming groups will rely more heavily upon sources outside of the lab, and better performing groups more upon sources within the lab.

Table III shows the frequency distributions for each channel of messages leading to higher and lower rated solutions to the 32 subproblems. Since expected frequencies in individual cells are too small for statistical test, the channels were aggregated into three categories: those within the lab, (technical staff, company research, analysis & experimentation, and personal experience); those which are outside of the lab (literature, external sources, and vendors); and the customer.[5] (Table IV)

TABLE IV

Sources of Higher and Lower Rated Solutions
(16 Subproblem Pairs; Channels Combined)

	number of higher rated solutions	number of lower rated solutions
channels outside of the laboratory (L + ES + V)	11	15
channels within the laboratory (TS + CR + A/E + PE)	19	15
customer	12	11

5 The customer is treated as a separate category since he is obliged to provide information to both teams impartially.

TABLE V

Comparison of Sources of All Technical Alternatives Considered by Groups Submitting Solutions Receiving Higher and Lower Ratings (16 Subproblem Pairs)

	information channel	higher rated subproblem solutions	lower rated subproblem solutions
channels outside the laboratory	literature	4	6
	external sources	2	10
	vendors	8	12
	customer	27	29
channels within the laboratory	technical staff	3	1
	company research	4	1
	analysis & experimentation	32	23
	personal experience	2	3
	unknown	3	6

While the trend is in the predicted direction, a chi-square test shows the difference in performance of the aggregate channels to fall short of statistical significance ($X^2 = 1.15$, $p>0.50$).

Although no strong conclusions can be reached concerning the direct sources of the solutions submitted by the better and poorer performing research teams, there is a possibility that significant differences exist in their general information-gathering behavior.

To test this, the sources of all alternatives considered by teams submitting higher and lower rated solutions are tabulated in Table V. Expected frequencies are again too low for test, so channels are aggregated as before (Table VI). A chi-square test rejects the null hypothesis of no difference at the 0.05 level of significance ($X^2 = 8.71$).

Poorer performing teams rely much more upon vendors, consultants and other persons outside of the laboratory for their ideas. Better performers use their technical staff to a greater extent; profit from information generated by other research programs within the company; and generate more alternatives through their own analysis and experimentation. The two differ little in their use of the literature or in their reliance upon their own personal experience.

Channel Ratings

Since a numerical score ranging from 1 to 5 was assigned each solution by the technical evaluator, this score could be assigned to the channels

TABLE VI

Sources of All Technical Alternatives Considered by Groups
Submitting Higher and Lower Rated Solutions
(16 Subproblem Pairs; Channels Combined)

	subproblems with higher rated solutions	subproblems with lower rated solutions
channels outside of the laboratory (L + ES + V)	14	28
channels within the labcratory (TS + CR + A/E + PE)	41	28
customer	27	29

whence each solution originated, and mean ratings derived for the channels. To control for differences among evaluators, each evaluator's scores were normalized on the basis of the rank given each channel. Ranks were then weighted by the number of observations on which they were based and mean ranks computed for each channel across all evaluators.[6]

The ranking of information channels, thus derived, is shown in Table VII.

TABLE VII

Rank Ordering of Information Channels on the Basis of Numerical Evaulation of Solutions

1. company research
2. technical staff
3. personal experience
4. customer
5. literature
6. vendors
7. external sources
8. analysis & experimentation

DISCUSSION

The results indicate a rather serious misalignment in the use of information channels by R & D personnel. There is apparently a substantial variation in the effectiveness of information channels, as measured at two

[6] Since no evaluator provided scores for all channels, a measure of agreement or concordance among evaluators was not derived.

levels, but this effectiveness is not recognized and reflected in the frequency with which the channels are used. Table VIII illustrates this point with a rank ordering of channels on the basis of the three measures used in the study (message acceptance rate by the engineer, customer evaluation, and relative use of the channel).

TABLE VIII

Rank Ordering of Information Channels
on the Basis of Three Performance Measures

	Message acceptance rate by the engineer	Customer evaluation of solutions	Frequency of use
1.	company research	company research*	analysis & experimentation
2.	technical staff	technical staff*	customer
3.	external sources	personal experience	vendors
4.	personal experience	customer	personal experience
5.	literature	literature	external sources
6.	vendors	vendors	literature
7.	analysis & experimentation	external sources	technical staff
8.	customer	analysis & experimentation	company research

*tied

Aside from the placement of two channels, the engineer and customer evaluations are remarkably similar. Even the two exceptions are quite plausible differences. The customer tends to rate his own ideas considerably higher than does the engineer. And engineers apparently overrate ideas

originated by external sources. When an engineer resorts to a consultant, he quite likely tends to overestimate the consultant's competence in the area and, as a result does not exercise sufficient skepticism in assessing the idea. With the customer's rating of his own ideas disregarded, the Spearman rank order correlation (r_s) between the two levels of evaluation for the remaining seven channels is 0.83 ($p = 0.01$).

Frequency of use, however, seems to run directly opposite to both of these ratings. As mentioned earlier, a comparison of acceptance rate with use shows an almost perfect reverse ordering; in comparing customer evaluation with channel usage, $r_s = -0.67$ ($p<0.05$). Preference for one channel over another appears to result from some feature other than its actual usefulness. This other feature may well be, as Ackoff and Halbert (1958) found, the accessibility of the channel. Further research is needed into the causes of the preference for particular channels.

Comparing channels on the basis of their use and their contribution to both performance measures, we find analysis and experimentation and vendors to be clearly over-utilized, and technical staff and company research to be clearly under-utilized.

It is difficult to fathom the meaning behind the apparent over-utilization of analysis and experimentation. This is after all, what engineers are paid to do, and earlier evidence (p. 10) showed that better performing groups used this source more than poorer performers. Perhaps the low rating attained here is a reflection on the general quality of the analysis performed on the seven projects. With vendors, however, there is a clear moral. Certainly, good use can be made of information obtained through vendors. But in using vendors, it must be remembered that it is difficult enough for project engineers to understand the customer's needs and the range of values he is willing to accept; vendors are one step further removed and the difficulty increases non-linearly. Finding a vendor does not dispense with the need for good engineering in-house. Specifications must be drawn knowledgeably, and vendor activities must be closely monitored in order to assure proper use of the information available through this channel. The fact that vendor acceptance rate is low is evidence that the channel is used with some skepticism, but were the vendors to be made more clearly aware of what was desired of them, both their acceptance rate and customer evaluation might be improved.

The under-utilization of technical staff and company research agrees quite clearly with the finding that R & D groups submitting higher rated solutions rely more heavily, than do the poorer performers, upon sources within the laboratory.. This says quite a lot about the benefits to be derived from and the need for improving the communication flow within the lab itself. For example, technical staff who are knowledgeable in particular areas could be made more readily available for consulting by project members, and rewarded for the contribution which they make through this type of activity. The distribution of company documents resulting from R & D programs and company-sponsored research could be improved. Perhaps as the laboratory feels that it has attained a certain degree of competence

in an area, summary documentation could be prepared, presenting the state-of-the-art, the nature of the lab's capabilities and the names of key people who are available for consulting. This is frequently done for presentation to customer agencies, but how often is such documentation prepared specifically for in-house use?

Literature does not appear to be greatly used, nor does this appear to be out of line with the evaluation of ideas obtained from it. Perhaps the most outstanding result to be noted here is that very few of the literature citations are to the professional engineering or scientific literature. Most literature references are to trade publications and free-subscription (advertising-supported) technical magazines.[7] A rather serious problem may exist here, since these publications are outside the control of the professional societies and are open to the temptation of distortion toward the products of their heavy advertisers.

CONCLUSIONS

This study has demonstrated the feasibility of a new technique for measuring the performance of the technical communication system and evaluating the relative performance of information channels. The technique employs the vehicle of parallel R & D projects to provide a control over

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[7] While the fact that engineers rely little upon the literature will undoubtedly surprise some, it is a finding which is not unique to this study. Compare, for example, Scott and Wilkins (1958) and the report of the O.E.E.C. (1958).

the substance of the problem and a relative evaluation of solutions. Data are gathered by means of Solution Development Records and lengthy interviews with the engineers. The ideas considered for solution to each problem are thus associated with the channels whence they came, and measures of performance are generated for the channels.

The principal conclusions of the study are:

1. Better performing groups rely more than the poorer performers upon sources within the laboratory (the technical staff, other company research programs, and their own analysis and experimentation) as contrasted with sources outside the lab.
2. There is a serious misalignment between the quality of the ideas generated through the eight channels studied, and the frequency with which these channels are used by engineers.
3. Based upon relative acceptance of messages by the design engineers and customer ratings of the accepted messages, it appears that such channels as vendors, and analysis and experimentation are over-utilized relative to their effectiveness and information from company research programs and experts on the technical staff are under-utilized.
4. Literature is not greatly used, and what is used consists primarily of trade publications rather than professional journals.

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